MOBILE ROBOT POSE TRACKING FOR PERFORMANCE ANALYSIS

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ABSTRACT: The NIST Construction Metrology and Automation Group, in cooperation with the NIST Intelligent Systems Division, is researching robotic structural steel placement as part of a project to develop an Automated Steel Construction Testbed. The initial phase of this project centers on tracking a six degree-of-freedom robotic crane with a laser-based site measurement system to provide position feedback for autonomous steel assembly. Follow-on efforts will use a high-resolution LADAR scanner co-registered with the site measurement system to provide world model data. The combination of these two advanced metrology systems provides an opportunity for testing performance characteristics of mobile intelligent systems.

KEYWORDS: intelligent control, intelligent systems, performance metrics, 3-D coordinate measurement systems

1.0 INTRODUCTION

The NIST Construction Metrology and Automation Group (CMAG) is developing a robotic structural steel placement system for the testing and validation of advanced tools, methodologies, and standards for automated steel construction. This system, the first phase of the NIST Automated Steel Construction Testbed (ASCT), will demonstrate autonomous "pick and place" assembly of structural steel components using a six degree-of-freedom (DOF) robotic crane and an external pose estimator [1].

The base platform is the NIST RoboCrane, which is an inverted Stewart platform parallel link manipulator. The pose (position and orientation) estimator, a laser-based site measurement system (SMS), provides absolute cartesian position feedback to RoboCrane's Real-Time Control System (RCS) for trajectory planning and dynamic control. A world map of the robot work volume including target components and obstacles is created prior to operations using the SMS.

Future work on the ASCT will include incorporating a high-resolution LADAR (laser detection and ranging) system to create and update the world map, thus eliminating the requirement for a human operator to digitize the scene with the SMS prior to operations. The LADAR scans will be meshed and then registered to the SMS.

The use of an independent, external measurement system to track a mobile robot within an environment mapped and registered to the tracking system provides interesting opportunities for conducting mobile robot performance analysis. In a future experiment, the NIST Intelligent Systems Division (ISD), in cooperation with CMAG, will use this combination of metrology instruments to test the navigation and sensing systems on board the NIST robotic HMMWV test vehicle as part of the U.S. Army's Experimental Unmanned Ground Vehicle System (DEMO III) program.

This paper discusses the development of the robotic structural steel placement system and a proposed test methodology for the DEMO III sensor package performance analysis.

2.0 ASCT

2.1 Operational Concept

Four laser transmitters are positioned on the site perimeter to illuminate the work volume of RoboCrane with reference beams (Figure 1). A digital model of the construction plane including any obstacles is created using the SMS digitizing wand.

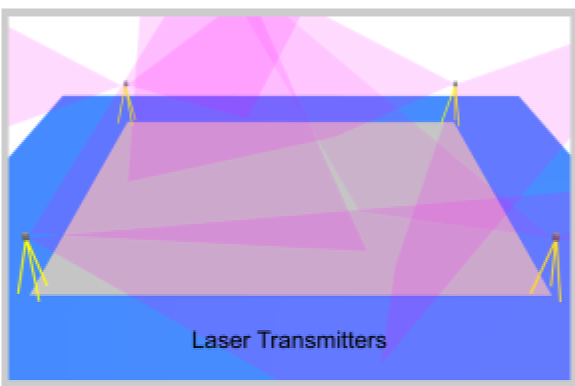

Figure 1: Illuminating the Work Site with the SMS.

This world model is then updated with the positions of the as-built structure and the target beam through a process of automatic part identification (barcode), part model database access, and part fiducial point measurement using the mobile digitizing wand (Figure 2).

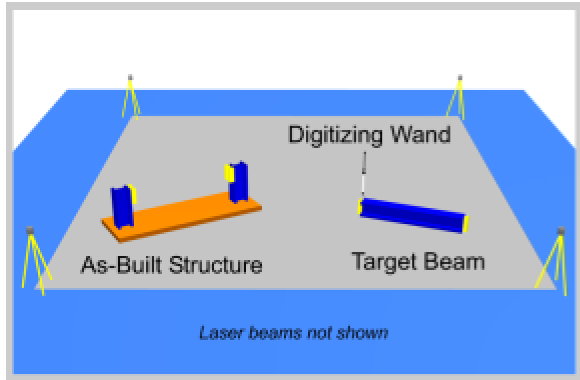

Figure 2: Measuring component locations with the SMS digitizing wand.

The current pose of RoboCrane is measured from onboard SMS sensors, and the path planner calculates the required transformations for beam pickup and delivery. RoboCrane then executes the movements (Figure 3).

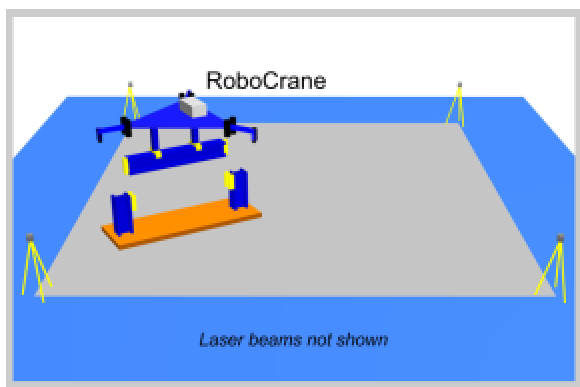

Figure 3: Steel beam placement with RoboCrane.

2.2 RoboCrane

RoboCrane is an innovative cable-driven manipulator invented by the NIST Intelligent Systems Division and further developed and adapted for specialized applications over a period of several years [2,3,4,5]. The basic RoboCrane is an inverted Stewart platform parallel link manipulator with cables and winches serving as the links and actuators, respectively. The moveable platform, or "lower triangle," is kinematically constrained by maintaining tension in all six cables that terminate in pairs at the vertices of the "upper triangle." This arrangement provides improved load stability over traditional lift systems and enables 6 DOF payload control.

The version of RoboCrane used in the ASCT project is the Tetrahedral Robotic Apparatus (TETRA) (Figure 4). In the TETRA configuration, all winches, amplifiers, and motor controllers are located on the moveable platform. The upper triangle only provides the three tie points for the TETRA cables, allowing the device to be retrofitted to existing overhead lift mechanisms.

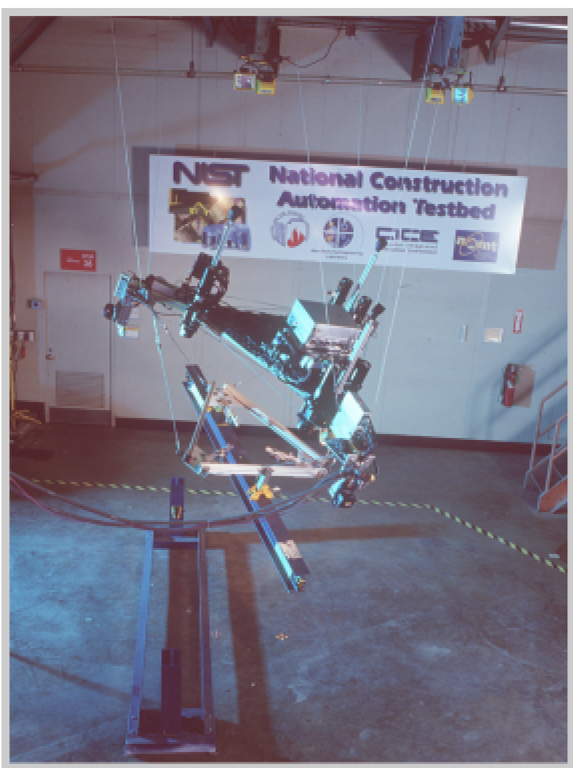

Figure 4: RoboCrane – TETRA Configuration

2.3 Site Measurement System

The SMS uses commercially available positioning technology (*3D-I*) produced by Arc Second, Inc. in the *Constellation* and *Vulcan* product families. (*3D-I*, *Constellation* and *Vulcan* are registered trademarks of Arc Second, Inc.) These systems use stationary, active-beacon laser transmitters and mobile receivers to provide millimeter-level position data.

2.3.1 SMS Description

Both *Constellation* and *Vulcan* systems use eye-safe laser transmitters to triangulate the position of a tuned optical detector. Each transmitter emits two rotating, fanned laser beams and a timing pulse. Elevation is calculated from the time difference between fan strikes. Azimuth is referenced from the timing pulse. The field of view of each transmitter is approximately 290° in azimuth and +/- 30° in elevation/declination. The recommended minimum and maximum operating ranges from each transmitter are 5 m and 50 m, respectively.

Line-of-sight to at least two transmitters must be maintained to calculate position. The *Constellation* receivers each track up to four transmitters and wirelessly transmit timing information to a base computer for position calculation. The *Vulcan* system is a self-contained digitizing tool with two optical receivers on a rigid pole. A vector projection along the line formed by the two optical detectors allows 3-D measurement of the tool tip. *Vulcan* can track only two transmitters at one time; however, the transmitter selection can be manually switched between any of the four available. Recovery of positional data following momentary signal blockage takes approximately one second.

2.3.2 Prior *3D-I* / Mobile Robot Integration

Early efforts to use this laser technology for mobile robot navigation showed that although the system was capable of guiding a mobile robot [6], its use was restricted due to loss of track at relatively low vehicle speeds [7]. Upgrades to the positioning technology continued and a successful combination of indoor 2-D map creation and autonomous navigation was demonstrated in a research project at the Rochester Institute of Technology [8] (Figure 5). Subsequently, a single receiver *Constellation* system was installed on an autonomous lawn mower at the Carnegie Mellon University Field Robotics Center and provided positional reference in a large outdoor setting [9].

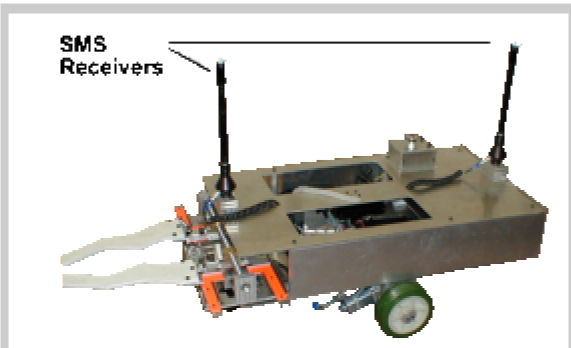

Figure 5: SMS Receivers on the RIT/SME "RC" Robot.

2.3.3 The SMS on RoboCrane

Three SMS receivers are mounted on RoboCrane at the vertices of the lower triangle (Figure 6). The receiver locations are registered to the manipulator during the initial setup process in the local SMS coordinate frame. For convenience, all measurements are calculated in the local SMS coordinate frame, though if required, mapping to an existing world coordinate frame could be accomplished. Receiver timing signals and diagnostic data are wirelessly transmitted to a base station computer running Arc Second's proprietary position calculation software. Position and SMS diagnostic information is polled at approximately 7 Hz using a NIST-developed data communications application. Position data from the three receivers are used to calculate RoboCrane's pose. Diagnostic data such as number of visible transmitters, excess signal noise or multipath reflections are also provided for each position calculation and is used to assess the quality of individual position fixes.

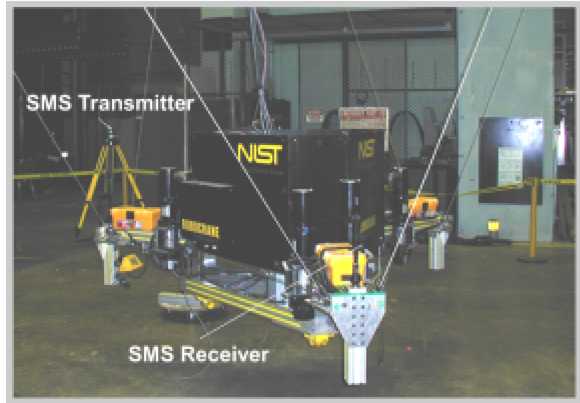

Figure 6: RoboCrane with SMS.

3.0 PERFORMANCE METRIC ANALYSIS OF THE DEMO III SENSOR SUITE

The NIST Intelligent Systems Division has provided research services developing control system architectures, advanced sensor systems, and standards to achieve autonomous mobility for various DOD unmanned ground vehicle programs including the Army Experimental Unmanned Ground Vehicle System (DEMO III) [10]. In a future experiment, high-resolution LADAR scanning and the SMS will be used to quantify the performance characteristics of the DEMO III sensor suite.

The test vehicle used by NIST is an Army HMMWV instrumented with a number of sensors (Figure 7). These include a LADAR range sensor that returns a 90° by 20° range image, a pair of color cameras for stereo imaging, a color camera, a line scan LADAR, and a wide-angle panoramic image mosaic obtained by stitching images from three color cameras. The vehicle also has an inertial navigation system (INS) and a GPS receiver.

An artifact field consisting of variable-sized box structures distributed within a nominal 30 m x 30 m area of clear terrain will be created on the

NIST grounds. CMAG will create a "ground-truth" digital map of the artifact field and then track the HMMWV test vehicle within that field.

Figure 7: NIST Robotic HMMWV Test Vehicle.

The artifact field will be scanned from several viewing angles using the using a high-resolution LADAR. The LADAR frame data will then be post-processed and manually meshed to create a multi-view map of the entire test area (Figure 8). The artifact field will also be measured using the SMS digitizing tool to create control points to overlay the SMS tracking data on the LADAR map.

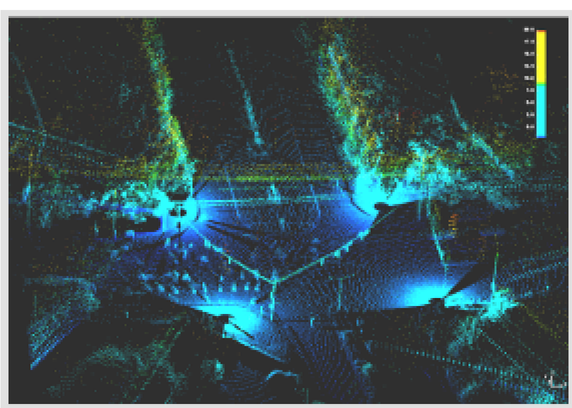

Figure 8: Sample High-Resolution Multi-Scan LADAR Image (Traffic Intersection).

Three SMS receivers will be mounted on the HMMWV test vehicle. These receivers will be mounted high on the vehicle to ensure each receiver has line-of-sight to at least two of the four transmitters located on the perimeter of the test field during tracking. Fiducial points on the vehicle will be measured to map the SMS receiver locations to the vehicle coordinate system. The HMMWV test vehicle will then traverse the test field at slow speeds and the track data will be written at ˜ 7 Hz. Track data from each receiver will then be post-processed to provide time-stamped vehicle pose (Figure 9).

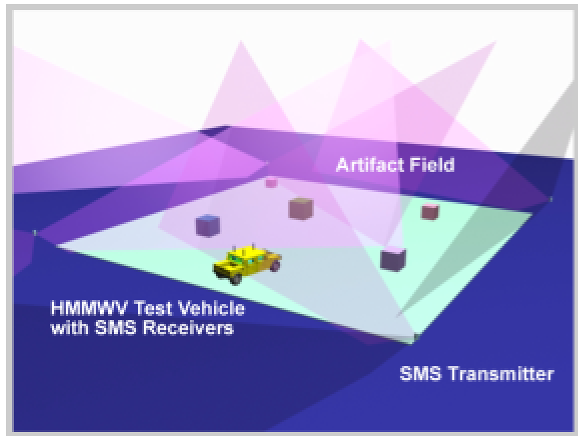

Figure 9: Test Vehicle on Artifact Field.

The 6 DOF vehicle track measured by the SMS will then be overlaid on the LADAR map. This will then be compared to the world map created by the DEMO III sensor suite to evaluate its performance. The performance of individual sensors and the performance of the system as a whole will be measured.

There are a number of measurement goals for the sensor characterization experiment. One is to see how accurately each of the sensors can measure the real terrain and the sizes, shapes, and positions of objects on it. Others are to see how well the sensors are registered and how well their positions in the vehicle's coordinate system can be determined. While the sizes of the objects within the test range can be measured accurately, the terrain is not entirely flat, and the high resolution LADAR will be used to determine ground truth. The SMS will be used to determine how well the INS system works.

Tables 1 through 5 provide manufacturer's performance data for the measurement systems that will be used in the test.

4.0 CONCLUSION

The combination of high-resolution LADAR imaging with a laser-based SMS provides an opportunity to create a "ground-truth" digital model of an autonomous vehicle's environment and then track the vehicle as it traverses, senses, and models that environment. The "ground-truth" map, complete with time-stamped vehicle pose, can then be compared to the platform's world model to quantify the performance of the on board navigation and sensing suite. A future experiment using the NIST HMMWV test vehicle on an artifact site will evaluate this method of mobile robot performance metric analysis.

5.0 REFERENCES

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Table 1: GDRS Area-Scan Ladar Specifications (HMMWV Test Vehicle).

Property	**Specification**
8 laser beams, 1 rotating mirror	With 8 facets
Scan resolution	32 lines x ?180 pixels
Scan coverage	20 x 90
Angular resolution	0.658 x 0.5
Maximum frame rate	60 scans/s but 30 scans/s

Range	5 m to 70m (vertical surface)
Range resolution/standard uncertainty	±7.6 cm / 15 cm
Data measurement rate	Range: 345,600 measurements/s
Day/Night Operation	Range Independent of ambient light

Table 2: Real-Time Performance of Applanix POS LV 420 Intertial Navigation Unit (HMMWV Test Vehicle).

POS LV 420-RT (using DGPS)	**GPS Outage Duration (minutes)**					
	0 min	**1 min**	**3 min**	**5 min**	**10 min**	**20 min**
X, Y Position (m)	1.0	1.5	1.75	2.0	2.5	3.5
Z Vertical Position (m)	1.5 to 2.0	2.0	2.0	2.0	2.5	3.0
Roll & Pitch (deg)	0.02	0.02	0.02	0.02	0.02	0.02
True Heading (deg) 0.02	0.02	0.02	0.04	0.06	0.10	0.20

Table 3: Performance of Applanix LV 420 with post-processing (HMMWV Test Vehicle).

POS LV 420 (post processed)	**GPS Outage Duration (minutes)**					
	0 min	**1 min**	**3 min**	**5 min**	**10 min**	**20 min**
X, Y Position (m)	0.02	0.12	0.40	0.75	1.5	2.5
Z Vertical Position (m)	0.03	0.15	0.50	0.65	1.0	2.0
Roll & Pitch (deg)	0.005	0.005	0.005	0.007	0.007	0.09
True Heading (deg)	0.02	0.02	0.02	0.03	0.035	0.035

Table 4: Manufacturer's Specifications - Riegl LMS Z210 Ladar.

Property	**Specification**
Scan coverage	80° x 330°
Angular stepwidth	0.072° to 0.36°
Angular readout accuracy	0.036°
Frame scan rate	1 °/sec to 15 °/sec
Minimum Range	2 m
Maximum Range	350 m (25 mm resolution, natural target)
Range resolution	25 mm or 50 mm, selectable
Standard uncertainty	Resolution + Distance error of = ±20 ppm

Table 5: Manufacturer's Specifications - *Constellation* and *Vulcan*.

Property	**Specification**	
	Vulcan	*Constellation*
Transmitter coverage	60° x 290°	60° x 290°
Transmitters required for position calculation	2	2
Maximum number of observable transmitters	2	4
Nominal Laser rotation rate	40 Hz to 50 Hz	40 Hz to 50 Hz
Minimum Range	5 m	5 m
Maximum Range	50 m	35 m
Angular resolution	=90 µrad	=90 µrad
Data rate (position calculation)	10 Hz	7 Hz

Standard uncertainty (Instrument x,y,z – U66)	± (1 + D/10000) [mm] D (mm) - distance between transmitters	10*RSS (250, D*8) [µm] RSS- Root Sum Squares RSS(A,B) = $\{A^2+B^2\}^{1/2}$ D (m) –distance from farthest transmitter No point data averaging

DISCLAIMER: Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.